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A fully-coupled dynamic model for the fundamental shear horizontal wave generation in a PZT activated SHM system

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ABSTRACT

The fundamental shear horizontal (SH0) wave in plate-like structures is of great importance in structural health monitoring (SHM) applications due to its unique non-dispersive nature. Its generation or reception using piezoelectric (PZT) wafers, however, is always a critical and challenging issue. In this study, a theoretical model on the shear horizontal (SH) wave generation is established based on the continuum mechanics theory. The model considers the dynamic properties of a PZT actuator and its coupling with a host plate through a bonding layer, whose mechanical property is modelled by considering a continuous shear stress but different tangential displacements across the adhesive layer. Closed form solutions are obtained using the trigonometric series decomposition and the modal superposition method. The solution series are shown to exhibit fast convergence. The model, along with some typical physical phenomena, is validated through comparisons with the FEM and experimental results. Numerical analyses allow establishing a series truncation criterion, in relation to the size of the actuator and the wavelength of the SH0 wave. It is shown that the dynamic coupling between the PZT and the plate should be considered in the design of PZT-activated SH0 wave generation. Typical phenomena in different frequency regions and their impact on the SH0 wave generation are scrutinized and discussed. The proposed theoretical model is expected to provide a useful tool for the physical mechanism exploration, structural design and eventually system optimization for SH0 wave generation in SHM applications.

1. Introduction

The ultrasonic inspection based on guided waves, a combination of the wave emission and the ultrasonic characterization, has shown its effectiveness for structural damage detection and has been extensively applied in non-destructive evaluations (NDE) and the structural health monitoring (SHM) [1–4]. Conventional guided waves include Lamb waves with symmetric and anti-symmetric modes and shear horizontal (SH) waves in plates. Among numerous techniques employed in the SHM, Lamb waves have been intensively explored, owing to their unique features such as strong penetration, long-distance transmission, omnidirectional dissemination and high sensitivity to damage etc. [3–6]. However, Lamb waves are dispersive in nature, with frequency-dependent phase and the group velocities. Waves are therefore distorted during propagation, which increases the complexities for the signal processing, especially when the wave packet interacts with cracks and/or defects. Compared with Lamb waves, one of the most appealing advantages of the fundamental shear horizontal (SH0) waves is its

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non-dispersive property. Therefore, the shape of the wave packet remains unchanged during the propagation, thus facilitating the interpretation of the received signals to some extent [7–8]. Moreover, the SH0 waves do not involve out of-plane particle displacements. The wave propagation is then less prone to the surrounding media, which is also attractive for SHM applications [9]. Hence, SH0 wave-based techniques show great potential in SHM applications.

The successful SH0 wave generation and a thorough understanding of the underlying physical mechanism are the prerequisite for the implementation of SH0 wave-based SHM techniques. Well-known methods include magnetostrictive transducers [10], electromagnetic acoustic transducers (EMAT) [11], interdigital PVDF [12,13] and shear horizontal piezoelectric wafer active sensor (SH-PWAS) [8,14]. Studies have been carried out to ensure the effective SH0 wave generation. Among these techniques, SH-PWAS is a popular choice, shown to be efficient and also cost-effective for SH0 wave generation in plates, with the piezoelectric transducers working in different modes, such as d_{15} [9], d_{35} [8], d_{24} [15–16] and d_{36} [7,17,18] modes. Specifically, for the d_{15} mode, with the poling direction of the piezoelectric wafer parallel to the surface of the plate and the electric field on the thickness direction, SH waves (including SH0 wave) can be generated and propagate along the direction perpendicular to the poling direction. For instance, a flexible d_{15} PZT transducer is used to generate SH0 waves with directionality in the low frequency range of 20–120 kHz [19]. Besides, to predict the directivity patterns of contact type ultrasonic transducers in the generation of guided waves, a novel 2D analytical model based on the Huygens's principle is proposed by Tiwari et al. [20], in which affiliated SH0 wave with 80 kHz is obtained through finite element modeling and verified by experiments. Recently, SH0 wave generation and reception using a synthesized face-shear deformation mode in a thickness-poled piezoelectric wafer have also been investigated [21].

Despite the vast FEM-based numerical investigations and experimental attempts on the SH wave excitation, there is still a lack of general theoretical method/model to systematically describe the generation process of the SH waves, which is the motivation and the contribution targeted by this paper. Such a model would allow revealing the mechanism of the SH wave generation on one hand, and providing guidance to the design of the SH-wave-based SHM system configurations in terms of the actuator size and excitation patterns to achieve the desired system performance on the other hand. Motivated by this, this work is dedicated to the development of such a theoretical model for further SHM applications.

In this paper, a theoretical model for the SH0 wave generation using d_{15} mode piezoelectric transducers is established based on the continuum mechanics theory, in which the transducer is bonded on a plate through an adhesive layer. Upon exciting the PZT actuator with an input voltage, SH waves are generated in the plate through the bonding layer. In the process, the dynamics of the PZT intervene and are coupled with the system, which is referred to as "dynamic coupling" in the following discussions. In the proposed model, the bonding layer between the PZT actuator and the plate is simulated through its thickness and shear modulus, instead of solving complex governing dynamic equations [22–24]. Analytical solutions, expressed in the form of trigonometric series, are then obtained, which can simultaneously satisfy the governing dynamic equations and the boundary conditions of the coupled PZT-plate system. The convergence of the series is first assessed, following by a comprehensive FEM validation process in both time and frequency domains. Additionally, experiments are carried out for further model validations and phenomenon verifications. After that, influences of the dynamic coupling on the system performance under different bonding conditions in different frequency ranges are investigated in detail to better understand the underlying physics and the impact on SHM system design.

2. Theoretical model

The two-dimensional model under investigation is composed of a PZT wafer (d_{15} mode), with a length $2a$, bonded on the surface of an infinite metal plate through a thin bonding layer, as shown in Fig. 1. The thickness of the PZT and the plate are denoted by h^p and h_s, respectively. The upper PZT belongs to transversely isotropic piezoelectric materials poled along the positive z direction which is determined from x and y by the right-hand rule and is assumed to be infinite in this model. The bonding layer, with parameters equivalent to an adhesive thickness typically in the range of 1–100 μm [25], is taken into account.

2.1. Governing equations

Driven by an alternating voltage imposed on the surfaces of the PZT, SH waves can be excited and propagate along ± x directions in the plate. Under the framework of the continuum mechanics theory, the displacement vector $\boldsymbol{u}$ and electric potential function φ in the PZT can be expressed as [26,27]

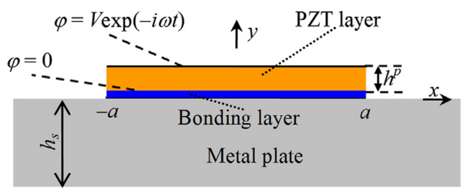

Fig. 1. Theoretical model.